OBSERVATIONS ON THE RATE OF THE EVAPORATION OF WATER OVER RESERVOIRS AND LAKES.

BY

PROF. FRANK H. BIGELOW.

Washington, Weather bureau,
1908.

U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU.

OBSERVATIONS ON THE RATE OF THE EVAPORATION OF WATER OVER RESERVOIRS AND LAKES.

By Prof. FRANK H. BIGELOW.

The rate of the evaporation of water in the open over large lakes and reservoirs has been the subject of much investigation, but the efforts to construct a suitable formula to represent this process have not been successful, because the so-called constants have resulted differently from the observations made in various places. It seems probable, from some work done during the summer of 1907, that we are dealing with a very complex variable, and that the process of evaporation is much more difficult to analyze than has been supposed. Pans were found to evaporate at very different rates, according to their location in the vapor blanket that always overlays any body of evaporating water. This seemed to have a depth of 40 feet at Reno, Nev., on the city reservoir, but it will vary with the size of the water surface and the climate in which it is situated. In a dry climate the blanket will overspread the water laterally only to a short distance, from 300 feet to one-fourth of a mile, according to the size of the sheet of water; in a moist climate ate it will be deeper and more extensive. It seems proper to collect statistics made on a uniform plan from different parts of the United States, from the reservoirs in the arid and the semiarid districts, as well as from those in the east where the vapor content of the atmosphere is large. These observations from all sections on a uniform plan should result in developing a formula in a practical form. To integrate a variable evaporation over a large lake is evidently a problem of considerable difficulty.

As is well known the rate of the evaporation of water over large reservoirs and lakes has been commonly discust by means of the Dalton formula, referred to the metric system,

$$E = C (e_w - e_d) + C (e_w - e_d) A w,$$

where,

E = the amount evaporated in the unit of time,
C = a constant of evaporation,
e_w = the vapor pressure at the water temperature,
e_d = the vapor pressure at the dew-point temperature,
A = a constant for the wind effect,
w = the wind velocity in kilometers per hour.

The constants will be changed for different units.

It has been found, from several careful researches, that the constants do not agree when the results are brought together, and it seemed to be of primary importance to discover the causes of this discrepancy. Consequently, as a preliminary step in preparation for the proposed campaign at the Salton Sea, it was deemed proper to investigate this point carefully. A short series of observations, covering the interval August 1 to September 15, 1907, was made at Reno, Nev., at the double reservoir, where five towers, 40 feet high, were erected in an east and west line, one on the central dike, one on each bank, and one in each field to the east and west, the outer towers being 2,200 feet apart. A

full account of the work may be found in the Monthly Weather Review for February, 1908, and it shows that the 29 pans placed in position were evaporating at very different rates, in accordance with their positions in the blanket of invisible vapor which covered that reservoir. The rate of evaporation seems to be controlled largely by the action of this invisible vapor covering a body of water, or an irrigated field, and consequently the term C in the Dalton formula is really a complex variable. Since pans evaporate differently in the middle of a lake from what they do on the edges, it is evident that the integration for the total evaporation over a given water surface is a difficult problem to solve practically. Even if the C-term were evaluated in any selected climate, as at the Salton Sea in the Colorado Desert, or at the reservoirs on the semiarid plateau, it would not be safe to transfer the results to reservoirs located in the central valleys or in the Atlantic States, without additional experience. Since the Salton Sea campaign will extend over several years, it has been thought prudent to facilitate the prosecution of evaporation studies in other places in the meanwhile, in order that observations of the right sort may be collected for discussion, referring to other climatic conditions. It is hoped that other observers who are interested will adopt a plan in harmony with the one here proposed, so that the observations may be comparable without further transformations.

The following formula is now suggested for trial, because it seems to work well for the Reno series:

$$E = Cf(h)\, e_d \frac{de}{dS} (1 + Aw),$$

where,

$Cf(h)$ = a variable function of the evaporation, changing with the height above the water surface and the distance from the center in a horizontal direction. It includes the diffusion and mixing process.

$\frac{de}{dS}$ = the rate of change of the vapor pressure with the change of the temperature of the water at the surface. It represents the Clayperon formula for the volume of vapor derived from the unit volume of water at the temperature S. It can be found from Table 43, Smithsonian Meteorological Tables, 1907.

A = the wind effect constant, 0.0175.

In order to give some idea of the variable function $Cf(h)$, *after the diurnal variation of the evaporation in a calm, and after the effect of the wind in increasing the evaporation have been removed*, the preliminary values for the Reno Reservoir are given.

(1) *The $Cf(h)$-term at the Reno towers.*

Height in feet.	No. 5, west.	No. 4, w. bank.	No. 3, middle.	No. 2, e. bank.	No. 1, east.
	Maximum or asymtotic value = 0.043.				
40	.041	.039	.037	.037	.038
20	.039	.036	.032	.035	.035
10	.036	.031	.025	.029	.032
0	.025	.024	.017	.024	.030

If the formula be put into the form,

$$E = Cf(h)\,\frac{1}{e_d}\,\frac{de}{dS}\,(1+Aw),$$

that is making the evaporation inversely proportioned to the vapor pressure of the free air, then the values of the variable become limited to a narrower range in the daily means, but this involves a larger range in the 3-hourly values, which is a disadvantage.

(2) *The $Cf(h)$-term at the Reno towers.*

Height in feet.	No. 5, west.	No. 4, w. bank.	No. 3, middle.	No. 2, e. bank.	No. 1, east.
40	1.418	1.355	1.230	1.307	1.263
20	1.387	1.311	1.181	1.185	1.235
10	1.309	1.340	1.063	1.175	1.171
0	1.168	1.141	0.838	1.114	1.168

These are the rough values of $Cf(h)$ which suggest a logarithmic or geometrical law for the diffusion, and this is a probable law under the physical conditions of the atmosphere.

The values of $\frac{de}{dS}$ can be taken from the following table:

Values of de/dS from the argument S, the water temperature.

S	$\frac{de}{dS}$	S	$\frac{de}{dS}$	S	$\frac{de}{dS}$
°C.		°C.		°C.	
0	0.33	10	0.61	20	1.07
1	0.35	11	0.65	21	1.14
2	0.38	12	0.69	22	1.20
3	0.40	13	0.73	23	1.26
4	0.42	14	0.77	24	1.33
5	0.45	15	0.81	25	1.40
6	0.48	16	0.86	26	1.48
7	0.51	17	0.91	27	1.56
8	0.54	18	0.96	28	1.64
9	0.57	19	1.02	29	1.72

The vapor pressure at the dew-point temperature, e_d, is taken from the Psychrometric Tables, with the arguments wet-bulb temperature (t_1) and the difference between the dry-bulb and the wet-bulb temperatures ($t-t_1$). The wind velocity in kilometers per hour is to be read from the metric anemometer. Professor Marvin has modified the ordinary Weather Bureau anemometer to register in kilometers per hour on the regular miles-per-hour dial.

The evaporation for the values of $Cf(h)$ given above is recorded in centimeters for 3-hour intervals.

INSTRUCTIONS FOR THE OBSERVATIONS.

Hours of observing.—The hours of observing should be 2 a. m., 5 a. m., 8 a. m., 11 a. m., 2 p. m., 5 p. m., 8 p. m., and 11 p. m. It is a great hardship to require so many readings daily, but without self-registering apparatus for the vapor pressure e_d, the evaporation E, and the temperature of the water surface S, it will be necessary for any thorogoing research. If the readings are made during the day from 5 a. m. to 8 p. m., with occasional observations at 11 p. m. and 2 a. m.,

the diurnal curve can be constructed. If the 3-hourly readings are made whenever convenient, and the sets collected in tables showing eight parts for the twenty-four hours, putting each observation in its proper place, after the lapse of time the collection will build up the mean diurnal conditions necessary for the discussion.

The following apparatus is convenient and easily procured.

Pans.—There seems to be no important effect on the rate of the evaporation due to the size of the pans. For floating in the water, iron pans, 4 feet in diameter and 10 inches deep, are suitable. Build a heavy wooden frame around the pan for a float and for stiffening it, hexagonal in shape, of 2″x 4″ pieces. Float the pan inside a breakwater 10′x 10′, made of 10″x 2″ planks on edge and braced together. Another breakwater outside this, two feet larger, is often required in strong winds and choppy waves. Three-foot pans can be used on the towers or stagings above the water surface. Three sets of two pans each ought to be sufficient for most studies, (1) in the middle of the water, (2) in the water near the bank, and (3) at some distance from the water, 300 to 500 feet. A 10-foot stand to carry the pans on land is easily made, with steps for mounting, and platforms for the lower and for the upper pans.

Gages for water depths.—A simple glass volumetric tube, drawn down to a narrow neck at one end, with millimeters engraved as a scale on the side, and fitted with a plunger on a fine wire makes a good measuring gage. Draw up the plunger, insert the tube in the water till it fills up to the proper level, plug the opening with the plunger, lift to the level of the eye and read the height on the top of the water. The difference of these readings from one observation to another gives the fall in the water due to the evaporation.

Water temperature.—Make a small raft with cross pieces. Attach a water thermometer, graduated in centigrade degrees, to the cross pieces so that it will float just submerged. A wet-bulb thermometer and a dry-bulb thermometer can also be added to float one-half an inch above the water surface, and from this the vapor pressure of the air can be computed quite near to the water surface.

Psychrometer.—An ordinary sling psychrometer for the dry-bulb and the wet-bulb temperatures, in centigrade degrees, is to be used for the vapor pressure of the free air near the pans.

Basket.—The psychrometer, the raft with its thermometers, and the gage tube, as well as a cup of water for moistening the rag, should all be placed in a basket and carried from pan to pan in making the observations. This will render any observed differences in the elements entirely free from the question of instrumental correction.

Order.—The observations should be arranged in a routine to follow the same order, so that the time-intervals may be equal, altho they may not occur at exactly the same hour and minute from day to day. Keep a careful note of the time of beginning and ending of a set of readings.

General directions.—The bottom of the floating pans should be supported by diagonal bracing so as to prevent any vertical movement of the bottom of the pan, due to changes in the temperature or to pressure upon the bottom of the pan from wave action. The temperature of the water, both in the pan and outside the pan, should be determined, or at any rate observations should be made so as to discover any variation, if it exists, which is likely to happen in the early forenoon and

late afternoon when the air temperatures are changing rapidly. The water surface in the floating pans, and in all the pans, should be maintained as near to the top of the pan as convenient, and the pan should be freely swept by the wind from all quarters.

The data which it is proposed to collect have no immediate reference to any formula, but they will be available in the studies which may lead to a final formula. It is particularly important that the observations be taken *every three hours* thruout the day, so as to eliminate the diurnal variation from the function which represents the fundamental evaporation capacity. The observations should be sorted into three sets of winds, 0 to 10, 10 to 20, and 20 to 40 kilometers per hour. In case it is not practicable to observe every three hours regularly, the observations can be arranged so that every complete set a of 3-hour group can be entered into a form, and the mean values, finally collected during the twenty-four hours, can be discust for a given interval, as a week or a month. The attached form is found to be convenient for the record, but the ruling should be wide in practise.

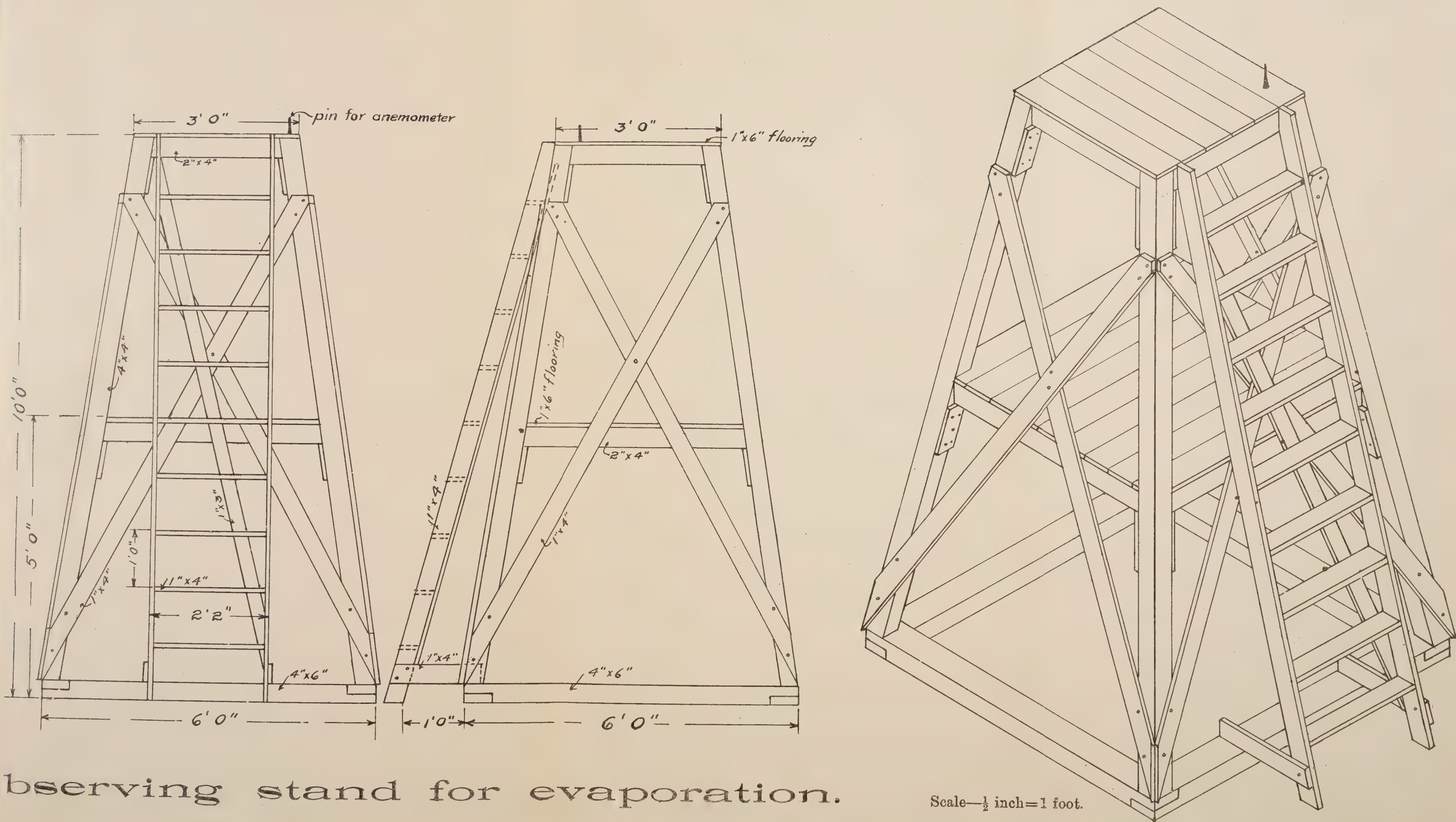
U. S. DEPARTMENT OF AGRICULTURE, WEATHER BUREAU.

EVAPORATION OBSERVATIONS.

Station,.......................... *Number of pan,*...... *Height of pan,*........

Year.	Hour,						Hour,						Hour,					
Month.	t	t_1	S	E	A	D	t	t_1	S	E	A	D	t	t_1	S	E	A	D
Day.																		
1																		
2																		
3																		
4																		
5																		
6																		
7																		
8																		
9																		
10																		
11																		
12																		
13																		
14																		
15																		
16																		
17																		
18																		
19																		
20																		
21																		
22																		
23																		
24																		
25																		
26																		
27																		
28																		
29																		
30																		
31																		

t=dry-bulb temperature of the air.
t_1=wet-bulb temperature of the air.
S=surface temperature of the water.
E=the height of the water in the pan.
A=the reading of the anemometer.
D=the direction of the wind.



Observing stand for evaporation.

Scale—½ inch=1 foot.